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Evaluation of Scaling Methods for Rotorcraft Icing

Jen-Ching Tsao
Ohio Aerospace Institute, Brook Park, Ohio

Richard E. Kreeger
Glenn Research Center, Cleveland, Ohio

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Jen-Ching Tsao
Ohio Aerospace Institute, Brook Park, Ohio

Richard E. Kreeger
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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Evaluation of Scaling Methods for Rotorcraft Icing

Jen-Ching Tsao
Ohio Aerospace Institute
Brook Park, Ohio 44142

Richard E. Kreeger
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

This paper reports result of an experimental study in the NASA Glenn Icing Research Tunnel (IRT) to evaluate how well the current recommended scaling methods developed for fixed-wing unprotected surface icing applications might apply to representative rotor blades at finite angle of attack. Unlike the fixed-wing case, there is no single scaling method that has been systematically developed and evaluated for rotorcraft icing applications. In the present study, scaling was based on the modified Ruff method with scale velocity determined by maintaining constant Weber number. Models were unswept NACA 0012 wing sections. The reference model had a chord of 91.4 cm and scale model had a chord of 35.6 cm. Reference tests were conducted with velocities of 76 and 100 kt (39 and 52 m/s), droplet *MVD*s of 150 and 195 μm, and with stagnation-point freezing fractions of 0.3 and 0.5 at angle of attack of 0° and 5°. It was shown that good ice shape scaling was achieved for NACA 0012 airfoils with angle of attack up to 5°.

Nomenclature

A_c	Accumulation parameter, dimensionless
b	Relative heat factor, dimensionless
b_0	Stagnation-point relative heat factor
c	Airfoil chord, cm.
d	Cylinder diameter or twice the leading-edge radius of airfoil, cm
h_c	Convective heat transfer coefficient, cal/sec m^2 K
h_G	Gas-phase mass-transfer coefficient, g /sec m^2
K	Inertia parameter, dimensionless
K_0	Modified inertia parameter, dimensionless
L	Length proportional to model chord, cm.
LWC	Cloud liquid-water content, g/m^3
MVD	Water droplet median volume diameter, μm
n	Freezing fraction, dimensionless
n_0	Stagnation-point freezing fraction
p	Pressure, Pa
p_w	Vapor pressure of water in atmosphere, Pa
p_{ww}	Vapor pressure of water at the icing surface, Pa
Re_δ	Reynolds number of water drop, dimensionless
t	Temperature, °C
t_f	Freezing temperature, °C
t_s	Surface temperature, °C
T	Absolute temperature, K
V	Air velocity, kt
0_L	Weber number based on dimension L and water properties, dimensionless
α	Angle of attack, deg.
β	Collection efficiency, dimensionless
β_0	Stagnation-point collection efficiency
ϕ	Droplet energy transfer parameter, °C
λ	Drop range, m
λ_{Stokes}	Drop range if Stokes Law applies, m
Λ_f	Latent heat of freezing, cal/g
Λ_v	Latent heat of vaporization, cal/g
μ	Air viscosity, poise
θ	Air energy transfer parameter, °C
ρ	Air density, kg/m^3
ρ_i	Ice density, kg/m^3
ρ_w	Liquid water density, kg/m^3
σ	Surface tension of water against air, dyne/cm
τ	Accretion time, min

Subscript

R	Reference
S	Scale
st	Static
tot	Total

Introduction

Aircraft and component manufacturers must thoroughly test new products to determine the effect of icing on their performance. This testing is performed both during the design process and for certification purposes. Flight-testing is necessary but is expensive and can only be done when atmospheric icing conditions exist. Furthermore, it can be very time consuming to find in nature the extremes in the cloud drop size and liquid-water content envelope required for certification testing. Icing wind tunnels can simulate natural icing with water-spray and refrigeration systems and provide control of cloud conditions, temperature and airspeed to permit safe, convenient and relatively inexpensive testing.

Because of test-section blockage limitations, many components cannot be tested full size in an icing wind tunnel. Furthermore, facilities that simulate natural icing can provide only limited ranges of air speed, cloud drop size, and liquid-water content. A scaling method is a procedure to determine the scaled test conditions to produce the same result as exposing the reference model to the desired cloud conditions. When the reference (full-size) model is too large for a given facility, model-size scaling is applied, and when the desired test conditions are outside the facility operating capability, test-condition scaling is required. Constraints may also prohibit strict geometric scaling of sub-scale models.

Scaling methods consist of a set of equations that are used to determine the necessary scale test conditions, given the reference conditions, model size, and geometry that need to be simulated. Unlike the fixed-wing case where extensive research efforts to develop appropriate scaling methods (Refs. 1 and 2) have begun as early as in the 1950s and continue to the present, there is no single method that has been systematically developed and evaluated for rotorcraft icing scaling applications. The scaling parameters have not been adequately verified (Ref. 3), in part because there is no publicly available research-quality database with which to assess the validity of these methods in a rigorous manner. Scaling methodologies also play an important role in obtaining data for icing code development and validation (Ref. 4).

Recently, icing tests were performed in the NASA Glenn Icing Research Tunnel (IRT) to begin a preliminary evaluation of existing fixed-wing scaling methods for icing applications to representative rotor blades at finite angles of attack. All tests were made using NACA 0012 models at angles of attack of 0° and 5°. The constant 0_L method of determining scale velocity was used. Results will be presented for stagnation-point freezing fractions of 0.3 and 0.5 and for the two reference velocities. In addition, to support an ongoing research effort in developing scaling methods for super-cooled large droplet (SLD) conditions, it is necessary for the reference and scale *MVD*s to be all in the SLD regime.

Scaling Equations

The current recommended scaling methods, from References 1 and 2, for fixed-wing unprotected surfaces under Appendix C and SLD icing conditions would be a good candidate to begin the development of scaling method for rotorcraft icing study. These two references provide a detailed explanation of the rationale and derivations of the equations used to describe the similarity parameters involved in traditional fixed-wing aircraft icing. It also includes some validation data. A very brief summary of current understanding and practice of scaling methods is given here, and the reader is referred to these references for a more comprehensive discussion.

For traditional fixed-wing aircraft icing, various icing scaling studies over the past 50 years have shown that there are four most important similarity parameters affecting ice shape. They are:

(1) Accumulation parameter,

$$A_c = \frac{LWC\, V\, \tau}{d\, \rho_i} \tag{1}$$

(2) Stagnation-point collection efficiency β_0, for example Langmuir and Blodgett (Ref. 5) had shown the β_0 for small water drops across a cylinder of radius d to be a function only of the modified inertia parameter, K_0,

$$\beta_0 = \frac{1.40\left(K_0 - \frac{1}{8}\right)^{0.84}}{1+1.40\left(K_0 - \frac{1}{8}\right)^{0.84}} \tag{2}$$

This K_0 was defined by Langmuir and Blodgett to describe the inertia of drops in an air stream flowing around a body:

$$K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{\text{Stokes}}}\left(K - \frac{1}{8}\right) \tag{3}$$

In equation (3), K is the drop inertia parameter,

$$K = \frac{\rho_w\, MVD^2\, V}{18\, d\, \mu} \tag{4}$$

where d is the radius for cylindrical models or twice the leading-edge radius for airfoils. Also in equation (3) $\lambda/\lambda_{\text{Stokes}}$ is the drop range parameter, defined as the ratio of actual drop range to that if Stokes drag law for solid spheres applied. It is a function only of the drop Reynolds number, Re_δ

$$\text{Re}_\delta = \frac{V\, MVD\, \rho}{\mu} \tag{5}$$

Langmuir and Blodgett tabulated the values of their calculated range parameter. For convenience, those data had been curve-fitted to the following expression:

$$\frac{\lambda}{\lambda_{\text{Stokes}}} = \begin{pmatrix} 0.8388 + 0.001483\, \text{Re}_\delta \\ +0.1847\sqrt{\text{Re}_\delta} \end{pmatrix}^{-1} \tag{6}$$

(3) Stagnation-point freezing fraction, n_0. From Messinger's (Ref. 6) surface energy balance, the stagnation-point freezing fraction is

$$n_0 = \frac{c_{p,ws}}{\Lambda_f}\left(\phi + \frac{\theta}{b_0}\right) \tag{7}$$

The individual terms in this expression are ϕ, the water energy transfer parameter,

$$\phi = t_f - t_{st} - \frac{V^2}{2c_{p,ws}}, \tag{8}$$

θ, the air energy transfer parameter,

$$\theta = \left(t_s - t_{st} - r\frac{V^2}{2c_p} \right) + \frac{h_G}{h_c} \left(\frac{\frac{p_{ww}}{T_{st}} - \frac{p_{tot}}{T_{tot}} \frac{p_w}{p_{st}}}{\frac{1}{0.622} \frac{p_{tot}}{T_{tot}} - \frac{p_{ww}}{T_{st}}} \right) \Lambda_v \tag{9}$$

and b_0, the relative heat factor, introduced by Tribus, et al.(Ref. 7) At the stagnation line, it is:

$$b_0 = \frac{LWC\, V \beta_0\, c_{p,ws}}{h_c}. \tag{10}$$

Equation (9) from Ruff (Ref. 8) includes compressibility effects. A simpler form without compressibility was used by Charpin and Fasso (Ref. 9) and others. Ruff's expression for θ was used in the calculations for all this work, but values found without compressibility are not significantly different for most icing conditions.

(4) Weber number,

$$\mathrm{We}_L = \frac{V^2 d \rho_w}{\sigma} \tag{11}$$

With scale model size selected, by matching scale and reference values of We_L the scale velocity can be determined. By matching β_0 the scale *MVD* can be found. References 1 and 2 also showed that the effects of temperature and *LWC* are not independent, but interact through the freezing fraction (i.e., the Olsen method). Therefore, with scale *LWC* chosen, by matching n_0 the scale temperature can be calculated. Finally, by matching A_c the scale accretion time can be established. For the scale test, then, only temperature, velocity, *MVD* and time have to be calculated from the known (reference) values of the similarity parameters.

While some of these similarity parameters are based on conditions that apply anywhere on the model, β_0 and n_0 are specific to the stagnation line of a clean model. Therefore, strictly speaking, scaling methods only apply at the stagnation line of a clean model. These parameters vary with chord-wise location and change as ice accretion modifies the geometry. Consequently, two assumptions are implied for scaling to be valid. The first is that with similar model geometries and similar flows around both reference and scale models, if β and n match at the stagnation point, they will tend to match everywhere on the model. This assumption has been verified for collection efficiencies in Reference 2. As for other airflow related issues: transition and roughness, for example, may not scale, and Re effects are assumed to have a minor influence on the final ice shape. Second, if the scaling is done successfully, the scale ice shape normalized by the model size will consistently agree with the reference for any accretion time starting with the clean model. Therefore, scale β and n will continue to match the respective reference values, even though those parameters are changing with time.

As for rotorcraft all the similarity considerations for fixed-wing aircraft icing should apply. In addition, compressibility and dynamic effects due to blade rotation must be considered. Also flow-field similarity requires matching of advance ratio and pitching settings as well as geometric similarity of the rotors. While future studies need to demonstrate scaling when aforementioned effects are present, it is necessary for the development of the appropriate scaling methods to begin with a much simplified flow and model configuration as a baseline and then proceed with additional physical effect of importance one at a time in testing. This could allow us to evaluate the significance of various physical effects unique to rotorcraft icing independently and reduces the complications from scaling testing.

Furthermore for rotorcraft icing scaling testing, it may be possible to divide the rotor blade into several radial regions according to rotating speed, as shown in Figure 1. Determination of the local ice shape would come from tests performed at various speeds to represent each radial location.

Therefore in this study the focus will be on the main rotor to address scaling, and the baseline configuration is a 2–D flow over a generic rotor blade airfoil at a prescribed angle of attack that can simulate local flow conditions along the blade at various radial locations. The models chosen are the symmetrical NACA 0012 airfoil of different chords.

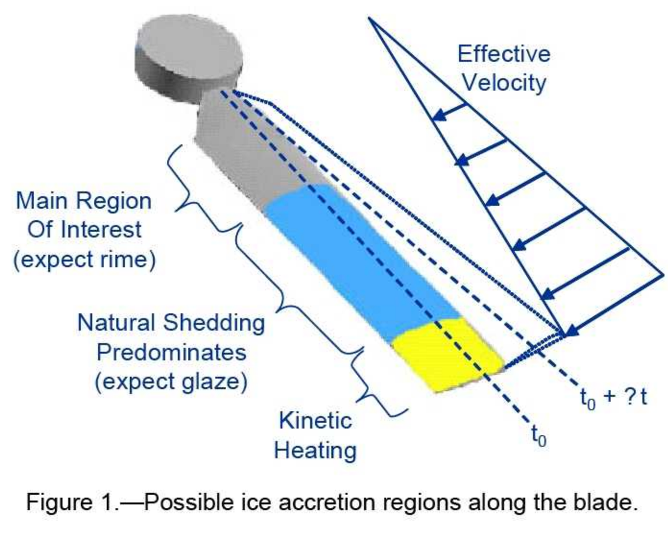


Figure 1.—Possible ice accretion regions along the blade.

Test Description

The icing tests were performed in the NASA Glenn Icing Research Tunnel (IRT). The IRT is a closed-loop, refrigerated, sea-level tunnel with a 1.8 m by 2.7 m rectangular test section. The icing cloud is generated by operating 10 spray bars, a configuration in use since 1998.

The IRT cloud calibrations for both Appendix C and SLD conditions used for these tests were performed in the summer of 2008. The *LWC* measurements were made using icing blade method as reported previously (Ref. 10). However, during the 2008 calibration there was not enough time to perform *MVD* measurements. The *MVD*s reported in this paper are based on an analysis of the *MVD* calibration data completed in February, 2006. In addition, because only a few specific *MVD-LWC* combinations at speeds of 100, 150, 200 and 250 kt (51, 77, 103 and 128 m/s) have been calibrated to date in the SLD regime, additional *LWC* measurements for SLD conditions were made in the IRT on September 22, 2008 with an icing blade. Therefore SLD tests are constrained to these particular conditions.

The models used were NACA 0012 airfoil sections with chords of 91.4 and 35.6 cm. The 91.4-cm-chord airfoil is pictured in Figure 2. It was a full-span, fiberglass model and served as the reference model. The 35.6-cm-chord scale model was of 61-cm span and made of aluminum. It was mounted vertically between splitter plates at the center of the IRT test section as shown in Figure 3. The supports permit changing the angle of attack. Although no angle-of-attack sweeps are planned for any of the present tests, models need to be rotated to align with airflow using external pressure belts wrapped around the model leading edge at specified chord-wise locations along the tunnel vertical center plane. An angle of attack of 5° is planned specifically; both reference and scale models were rotated to align with the airflow by matching the corresponding c_p curve using the external pressure taps on the models. Horizontal lines at the leading edge indicated tunnel center and ±2.5 cm from the center as visual guides for locating ice tracings. Both SLD and Mod-1 nozzles were used. Also because of the quick start capability of the current IRT spray system, the models were not shielded during the initiation of the spray.

In preparing for a test, the temperature and airspeed in the test section and the air and water pressures on the spray manifolds were set. When these conditions had stabilized, the spray nozzle valves were opened to initiate the spray. The spray was timed for the required duration, and then turned off. The fan was brought to a full stop and the researchers entered the test section to document the ice shape with hand tracings. Close-up photographs were also taken with a hand-held digital camera.

To record the ice shapes, a thin slice was first melted through the ice normal to the model surface. A cardboard template was then placed into this slit and an outline of the ice shape traced by pencil, giving a two-dimensional cross section of the ice. Tracings were taken at the vertical center of the tunnel (91 cm from the floor) and at 2.5 cm above the center. The ice shapes so recorded were digitized using an automated line-following feature in the image-analysis software, SigmaScan Pro (Ref. 11). Results from test entries in 2008 and 2009 will be presented. Since the shape differences between the two tracing locations were never significant, only centerline shapes will be reported here.

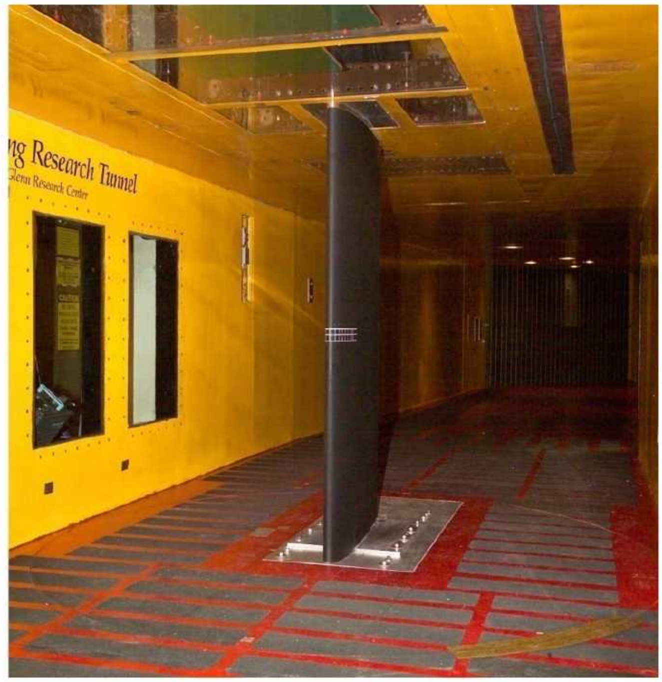


Figure 2.—91.4-cm chord model in the IRT test section.

Figure 3.—35.6-cm chord model in the IRT test section.

Uncertainty Analysis

Estimates of the uncertainty in the reported average conditions were made by considering inherent errors of instruments, temporal fluctuation and spatial variation of the instrument readings in the test section, and uncertainty in tunnel calibration of *MVD* and *LWC*. Recorded air temperature was believed to be accurate to ±0.2 °C, although variations during the period of an icing spray increases the uncertainty for reported average temperatures to about ±0.5 °C. The uncertainty in air velocity was estimated to be ±2kt. For Appendix-C conditions the net uncertainty in *MVD* was estimated at ±12 percent. For SLD conditions it may have been as much as ±20 percent. These uncertainties are not referenced to an absolute value of *MVD*, which is unknown. Repeatability and scatter in the *LWC* calibration data suggests the uncertainty is about ±12 percent for both Appendix C and SLD conditions.

The test-parameter uncertainties were used to estimate the following uncertainties in the similarity parameters for the SLD tests the uncertainties were: 2 percent in β_0, 12 percent in A_c, 10 percent in n_0 and 3 percent in 0_L.

Results

A preliminary evaluation of the angle of attack effect on scaling performance is shown in Figure 4 to Figure 7, which compare reference and scale ice shapes obtained for $\alpha = 0°$ (part (a) of each figure) with those at $\alpha = 5°$ (part (b) of each figure) for stagnation-point freezing fraction of 0.3 and 0.5 at reference velocities of 76 and 100 kt. For each figure, reference ice shapes are shown shaded, while the scale shapes are indicated by a solid line. The table below each figure gives the test conditions and similarity parameters for each pair of reference and scale tests. The conditions given are the average conditions recorded over the duration of each test, which can sometimes differ slightly from the planned set points. The parameters in the tables were calculated from these average conditions.

Stagnation Freezing Fraction of 0.3

Figure 4(a) and (b) shows reference and scale ice shape comparisons at 0° and 5° AoA with the constant 0_L method. The same reference icing condition was used for both comparisons. The reference model size, velocity and *MVD* were 91.4 cm, 76 kt and 147 μm.

In Figure 4(a) the scale and reference values of β_0, n_0, and 0_L matched within 5 percent and the values of $\beta_0 A_c$ were just within 8 percent. As demonstrated from previous scaling work for $\alpha = 0°$, the size and shape of the reference ice were well simulated by the scale test in the leading-edge region. In Figure 4(b) the scale and reference values of β_0, n_0 and 0_L matched within 2 percent and the product $\beta_0 A_c$ agreed only within about 17 percent. The scale ice shape closely simulated the reference main ice shape and feather region, however the size of the scale ice was relatively larger than the reference ice. Post data analysis indicated that the actual spray time for 09-29-08 run 2 (see Figure 4) was only 89 percent of the planned value. This disagreement explains the difference observed in the leading-edge ice thickness for this pair of shapes.

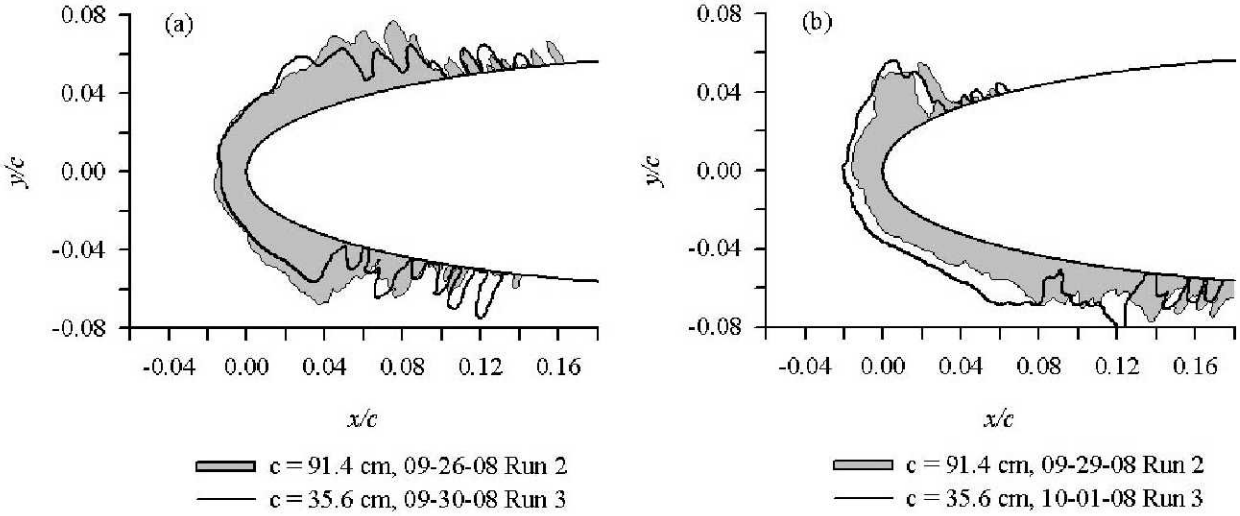
In addition, Figure 5(a) and (b), gives similar ice shape comparison results for a higher reference velocity of 100 kt with the 91.4-cm-chord 198-μm-*MVD* reference conditions scaled to 35.6 cm. In both cases (i.e., $\alpha = 0°$ and $\alpha = 5°$), the scale and reference values of β_0, $\beta_0 A_c$, n_0 and 0_L matched within 2 percent. The 35.6-cm-chord scale tests produced main ice shapes in fairly good agreement with the reference. Even the sizes of large feathers adjacent to the main shape and the smaller feathers further aft were simulated reasonably well (except for a few larger feathers further aft on the lower surface in Figure 5(a)).

Stagnation Freezing Fraction of 0.5

Figure 6(a) and (b) each compare reference and scale ice shapes with the 91.4-cm reference conditions scaled to 35.6 cm at 0° and 5° AoA respectively. The same reference icing condition was used for both comparisons. The reference model size, velocity and *MVD* were 91.4 cm, 76 kt and 147 μm.

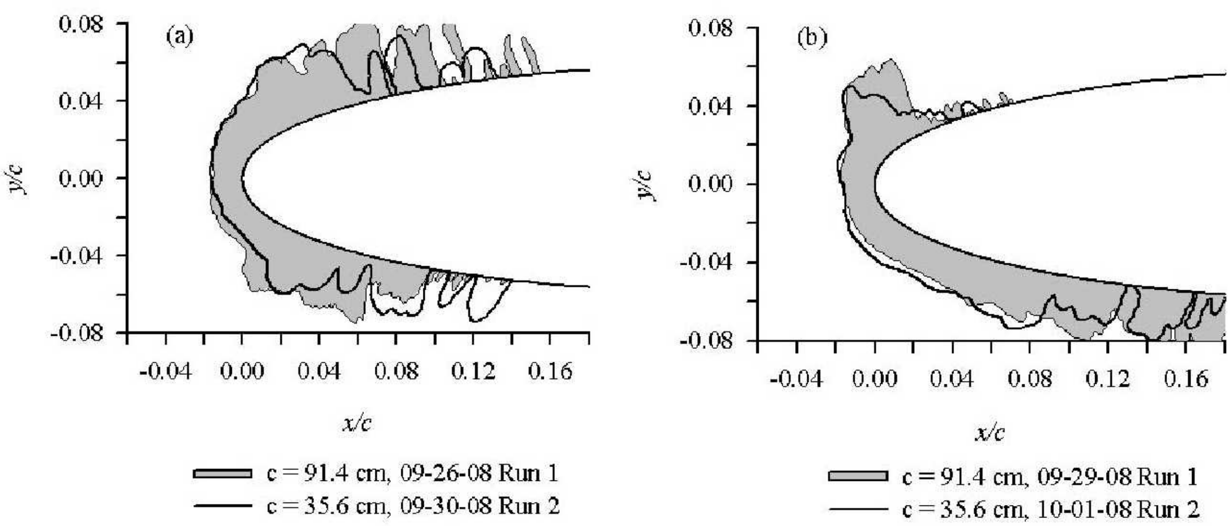
In Figure 6(a) the scale and reference values of β_0, $\beta_0 A_c$, n_0, and 0_L all matched within 2 percent. The size and shape of the reference ice were well simulated by the scale test in the leading-edge region. However, the scale (SLD) feathers were larger than the recorded in the SLD reference test. In a previous study (Ref. 12) with SLD icing scaling, the larger feather formation was observed for the Appendix C scale condition. It was speculated then that either there was something different about SLD icing physics compared with Appendix C or differences in the IRT drop-size distributions were responsible. Further study to isolate these large-feather conditions is needed to improve scaling performance. In Figure 6(b) the scale and reference values of β_0, n_0 and 0_L matched within 2 percent and the product $\beta_0 A_c$ agreed within 6 percent. The scale ice shape simulated the reference main ice shape and feather region fairly good, however the size of the scale feathers was still larger and the horn angle of the leading-edge main ice shape was also slightly different.

For a higher reference velocity of 100 kt, similar ice shape comparisons were made with the 91.4-cm reference conditions scaled to 35.6 cm and the results were shown in Figure 7(a) and (b). The reference *MVD* was 198 μm and the scale *MVD*'s was 87 μm. In both cases, the scale and reference values of β_0, n_0 and We_L matched within 2 percent. Reference and scale $\beta_0 A_c$ in Figure 7(a) matched within about 3 percent, and for Figure 7(b) agreed within 1 percent. The scale ice shapes for both cases were able to simulate the reference main ice shapes and feather regions well.



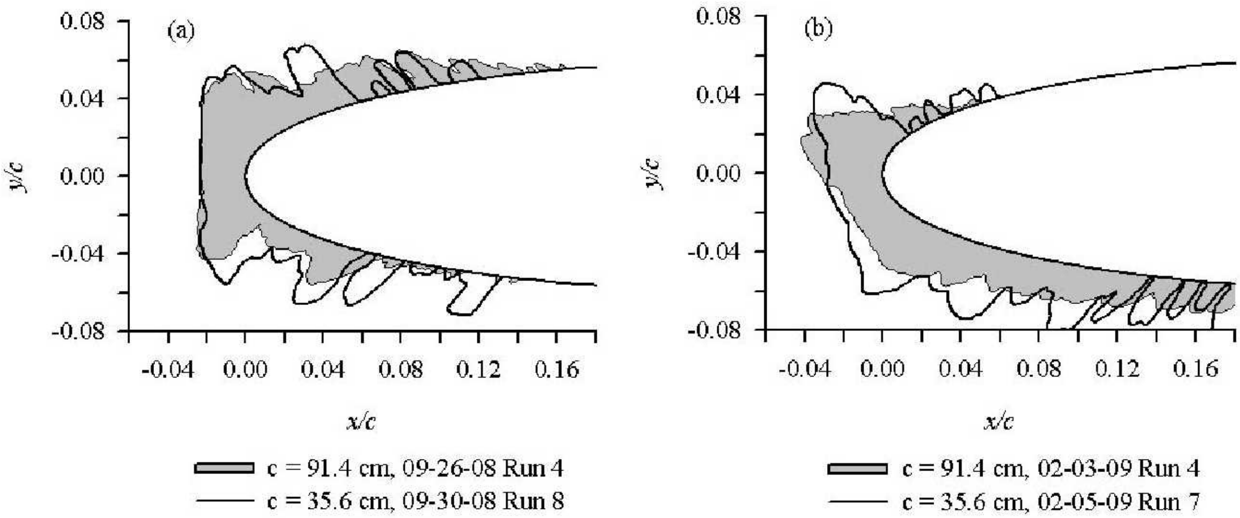
Date/Run	c, cm	α, °	t_{st}, °C	t_{tot}, °C	V, kt	MVD, µm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	0_L, 10^6
(a) 09–26–	91.4	0	–11.0	–10.2	76	147	1.68	11.2	94	1.66	1.56	0.32	0.67
09–30–08/3	35.6	0	–6.8	–4.9	120	68	0.95	5.3	94	1.80	1.69	0.31	0.66
(b) 09–29–	91.4	5	–11.0	–10.2	76	147	1.68	10.0	94	1.48	1.39	0.32	0.68
10–01–08/3	35.6	5	–6.8	–4.9	121	68	0.93	5.3	94	1.79	1.68	0.32	0.67

Figure 4.—Scaling from 91.4 to 35.6-cm-chord with 0_L matched. NACA 0012 airfoils at α = 0° and 5°; n_0, 0.3; V_R, 76 kt.



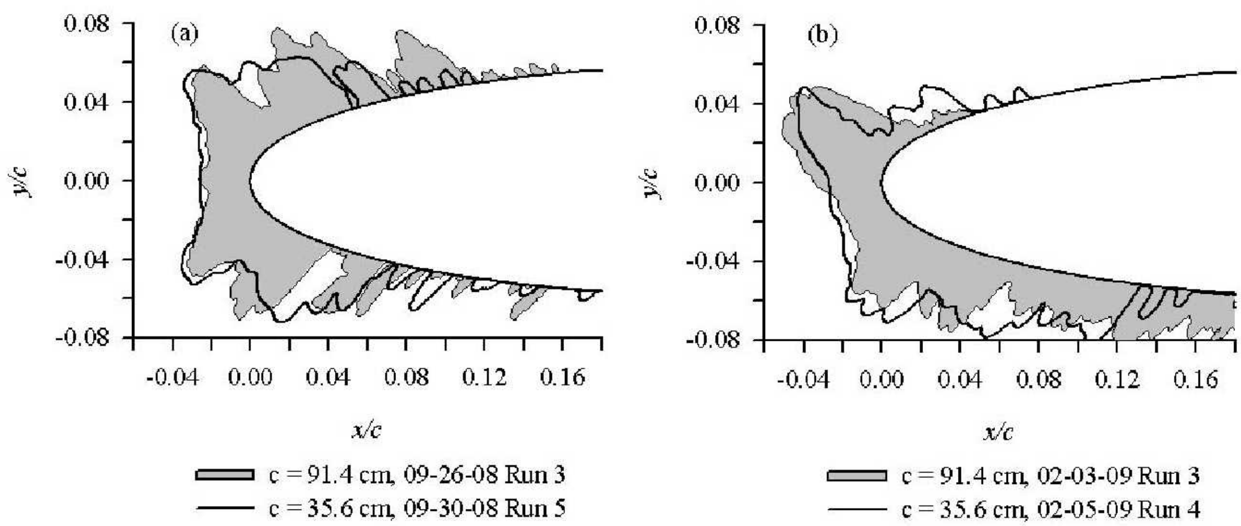
Date/Run	c, cm	α, °	t_{st}, °C	t_{tot}, °C	V, kt	MVD, µm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	0_L, 10^6
(a) 09–26–	91.4	0	–9.1	–7.8	100	198	1.08	14.0	96	1.75	1.69	0.31	1.17
09–30–08/2	35.6	0	–6.2	–2.9	159	87	0.57	6.6	96	1.80	1.73	0.31	1.16
(b) 09–29–	91.4	5	–9.1	–7.8	99	198	1.08	14.0	96	1.75	1.69	0.31	1.16
10–01–08/2	35.6	5	–6.2	–2.9	160	87	0.56	6.6	96	1.78	1.71	0.31	1.17

Figure 5.—Scaling from 91.4 to 35.6-cm-chord with 0_L matched. NACA 0012 airfoils at α = 0° and 5°; n_0, 0.3; V_R, 100 kt.



Date/Run	c, cm	α, °	t_{st}, °C	t_{tot}, °C	V, kt	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	0_L, 10^6
(a) 09–26–	91.4	0	–18.9	–18.1	76	148	1.77	11.2	94	1.76	1.66	0.52	0.68
09–30–08/8	35.6	0	–10.9	–9.0	121	68	0.94	5.3	94	1.79	1.69	0.52	0.67
(b) 02–03–	91.4	5	–18.7	–18.0	76	148	1.70	11.1	94	1.67	1.57	0.53	0.67
02–05–09/7	35.6	5	–11.0	–9.0	122	68	0.93	5.2	94	1.76	1.66	0.52	0.68

Figure 6.—Scaling from 91.4 to 35.6-cm-chord with 0_L matched. NACA 0012 airfoils at α = 0° and 5°; n_0, 0.5; V_R, 76 kt.



Date/Run	c, cm	α, °	t_{st}, °C	t_{tot}, °C	V, kt	MVD, μm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	0_L, 10^6
(a) 09–26–	91.4	0	–15.4	–14.1	100	198	1.07	14.0	96	1.75	1.69	0.52	1.18
09–30–08/5	35.6	0	–9.2	–5.9	159	87	0.57	6.6	96	1.80	1.73	0.51	1.16
(b) 02–03–	91.4	5	–15.3	–14.0	100	199	1.08	14.0	96	1.75	1.69	0.52	1.17
02–05–09/4	35.6	5	–9.3	–5.9	160	87	0.56	6.6	96	1.76	1.69	0.51	1.17

Figure 7.—Scaling from 91.4 to 35.6-cm-chord with 0_L matched. NACA 0012 airfoils at α = 0° and 5^0; n_0, 0.5; V_R, 100 kt.

These ice shape comparison results would suggest that the current recommended scaling methods for fixed-wing icing could be used for some generic rotor blade icing applications without any modification for some finite range of angle of attack. However, the data is very limited. Further evaluation is needed to establish the limiting conditions of such application in the IRT to improve scaling performance.

Conclusion

Icing tests were performed in the NASA Glenn Icing Research Tunnel and scaling results for 0° and 5° AoA were presented in this study. Evidence from ice-shape comparison shows that for NACA 0012 airfoils the ability to simulate a reference ice shape by scaling was not affected by the angle of attack in the range tested. Also, for the limited conditions of this study, there was no evidence of any difference in the fundamental formation mechanisms of either feather growth or horn formation on airfoil models at angle of attack.

Good ice shape scaling was achieved in this study by matching scale and reference values of the parameters β_0, A_c, n_0 and 0_L for NACA 0012 airfoils with angle of attack up to 5°. Model size ratio was 2.6:1 and freezing fractions covered the range from 0.3 to 0.5. The present SLD reference tests were made with velocities of 76 and 100 kt, and these conclusions may not be valid for higher velocities. Similar concern for larger static angle of attack should also be considered. Additional testing in the IRT is needed to document the limiting conditions and to evaluate other possible alternatives of scaling methods for such application to improve the current scaling knowledge and capability for rotorcraft icing.

Further icing testing on oscillating airfoils is planned in the IRT in coming years. This testing should provide a better evaluation of scaling performance in a much more realistic rotor blade operation environment.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This paper reports result of an experimental study in the NASA Glenn Icing Research Tunnel (IRT) to evaluate how well the current recommended scaling methods developed for fixed-wing unprotected surface icing applications might apply to representative rotor blades at finite angle of attack. Unlike the fixed-wing case, there is no single scaling method that has been systematically developed and evaluated for rotorcraft icing applications. In the present study, scaling was based on the modified Ruff method with scale velocity determined by maintaining constant Weber number. Models were unswept NACA 0012 wing sections. The reference model had a chord of 91.4 cm and scale model had a chord of 35.6 cm. Reference tests were conducted with velocities of 76 and 100 kt (39 and 52 m/s), droplet MVDs of 150 and 195 μm, and with stagnation-point freezing fractions of 0.3 and 0.5 at angle of attack of 0° and 5°. It was shown that good ice shape scaling was achieved for NACA 0012 airfoils with angle of attack up to 5°.

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